# Comparative Study on Milling Complex Curved Surfaces with Ball Nose End Mill and Toroidal End Mill

***Marius Cosma[1,*], Timotei Groza[2]***

**Abstract:** *This paper is based on a comparative study, for optimizing the process of finishing by milling complex curved surfaces. The objective of the work is to replace the ball nose end mills (BNEM with cutting edge disposal on spherical surface) with toroidal end mills (TEM with cutting edge disposal on toroidal surface), its purpose being to optimize time and costs of processing. This study will address aspects of the characteristics of the mills cutting tools used for milling complex curved surfaces, the description of spare parts requiring such processing from the company SC Ramira SA, Baia Mare, the implementation of the CAM/CNC programs and the analysis of the costs and time needed to finish specific surfaces with the two types of cutters.*

**Keywords:** *ball nose end mills (BNEM), complex curved surfaces, finishing by milling, toroidal end mills (TEM)*

## 1 INTRODUCTION

A ball nose end mill, also known as spherical end mill or ball end mill has a semi-sphere at the tool end and the cutting edge is disposal on spherical surface. Ball nose end mills are used extensively in the machining of complex surfaces of dies, molds for metal and for plastic injection molding in electronic industry, device's parts in automotive assembly and spare parts, aircraft components (especially frame sections and gas turbine with spline like profile) and in the defense industry.

The most critical area when using ball nose end mills is the center portion where the cutting speed is zero and chip evacuation is also critical due to the small space at the chisel edge.

Avoid using the center portion of a ball nose end mill as much as possible by tilting the spindle or the workpiece in 5-axes machine to get good cutting conditions.

Without considering the impact of the cutting edge with uncut chip in different tilted tool with adequate consideration of the chip cross section area variation and cutting forces, the result can lead to cutter failure and therefore lead to unnecessary waste of time, cost and poor surface quality.

The main criterion for assessing the quality of the machining is the scallop height, formed by the residual material between two successive paths of the tool, which mainly depends on the step-over distance $\mathbf{a_e}$ which is the distance, in a plane normal to the feed direction, between two successive paths of the tool (geometrically representation if feed per tooth $\mathbf{f_z < a_e}$, in Figure 1).

However, numerous studies have demonstrated the opportunity of using in complex surfaces milling, a toroidal end mill rather than a ball nose end mill or flat end mill [1].

As the flat end tool, the toroidal end mill allows under certain conditions, for a given step over distance, to obtain a lower scallop height than that allowed by the ball nose end mill. For a given scallop height at constant quality, it saves then a lot of productivity.

By combining the benefits of both of flat end and ball nose end tools, toroidal end mill appears to be the ideal compromise for finishing operation by end milling of freeform surfaces and global process optimization has not already been studied.

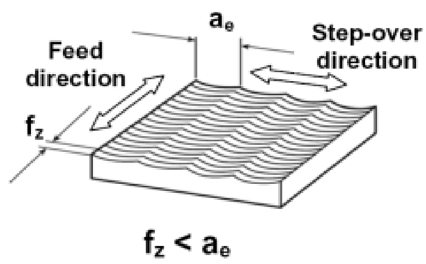



*Fig. 1. Scallop formed in BNEM and TEM*

## 2 EXPERIMENTAL PROCEDURE

### *2.1 Exposure of the problem to be solved*

This comparative study appeared as a need to reduce production costs for the processing of components in the automotive assembly device industry [2]. In order to achieve a forward orientation and fixation for the body parts for welding, the parts of the fastener must have the contact surfaces identical to the surface of the body element with which it comes into contact (Fig 2).

*Fig. 2. Automotive assembly device*

Examples of component parts from assembly devices that guide and fix body parts are shown in figure 3, where complex curved surfaces are marked with CCS.

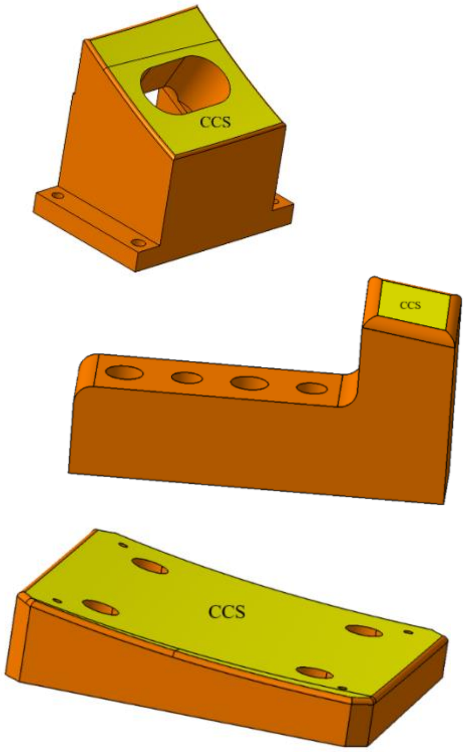



*Fig. 3. Parts from assembly devices*

The final milling of these parts is currently done with BNEM and the large number of tools passes on the curved surface necessary to obtain a surface with low roughness (surface that no longer requires manual finishing) determines to the use of a large number of milling tools and a very high CNC 5 axes machine time with important costs in the production process.

### *2.2 Experimental workpiece, tools and CNC center*

To carry out the experiment, a test workpiece C45 steel – DIN 17200 – EN 10083 Standard, (Fig. 4) was designed to have complex concave and convex surfaces to cover a wide range of surfaces.

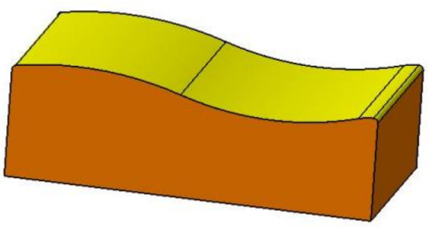


*Fig. 4. Experimental workpiece*

Surface processing was done with metal carbide mills of the same diameter D=10 mm from Iscar company [3], having the characteristics of Figure 5.

| BNEM<br>Z = 2 teeth | TEM<br>Z = 6 teeth |
|---|---|


*Fig. 5. Cutting tools*

Processing of the test workpieces was done on a milling center in 5 axes, model Okuma MU-400VA with the following main characteristics:

- maximum travels on axes: X = 762 mm
  Y = 460 mm
  Z = 460 mm
  A = -110º to +20º
  C = 360º
- maximum spindle speed 1500 rot/min
- maximum feed speed on X, Y, and Z is 32000 mm/min.

### *2.3 Cutting parameters and conditions employed*

For the finishing processing, the same cutting parameters were established for both cutters in accordance with the Iscar manufacturer's recommendations, as follows:

- cutting speed $v_c$ = 220 (m/min)
- tool diameter D = 10 (mm)
- spindle speed n = 7003 (rpm)
- feed per tooth $f_z$ = 0.05 (mm/tooth)
- axial depth of cut $a_p$ = 0.15 (mm)
- step over $a_e$ = 0.15 (mm)

The main differences between these tools are:

BNEM
- teeth number z = 2
- feed speed $v_f = n\ z\ f_z$ = 716 mm/min
- recommended tool life T = 360 min
- processing time/piece t = 45 min 42 sec
- price/tool = 85.3 €
- tool live = 360 min

TEM
- teeth number z = 6
- feed speed $v_f = n\ z\ f_z$ = 2100 mm/min
- processing time/piece t = 15 min 11 sec
- price/tool = 85.3 €
- price tool holder = 100 €
- tool live = 420 min

The CNC program for milling the complex curved surface was developed with the help of PowerMill 2020 software, used predominantly in Ramira CAM programming department, having numerous processing strategies and a high speed of generating processing trajectories and some aspects of the program are shown in Figure 6.

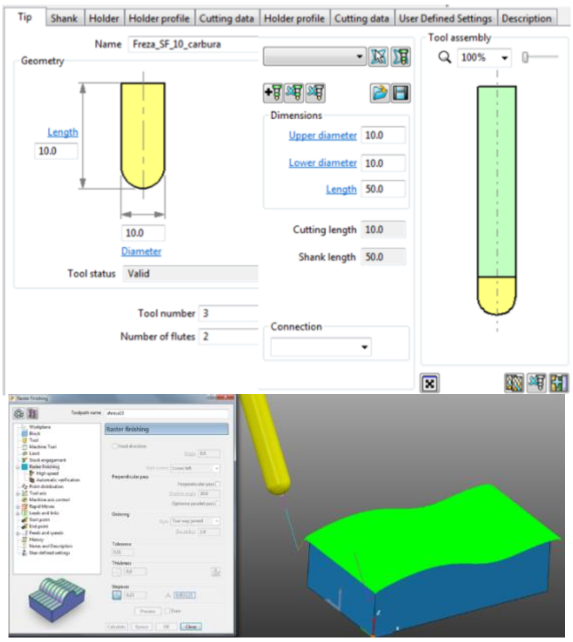



*Fig. 6. CAM aspects in PowerMill 2020*

To avoid cutting with the tip of the tool at BNEM and getting contact in the mean area of the toroidal cutting edge of TEM with the processed surface, was adopted, for booth tools, an angle of inclination of 30 degrees of the axis of the tool from the normal surface in perpendicular direction of the feed direction (Fig. 7).

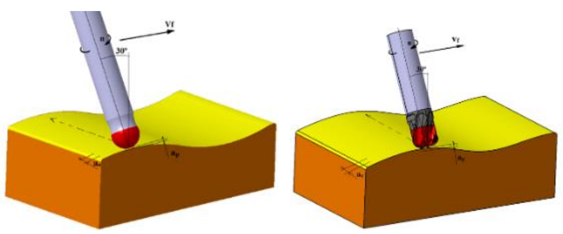


*Fig. 7. BNEM and TEM tools positions*

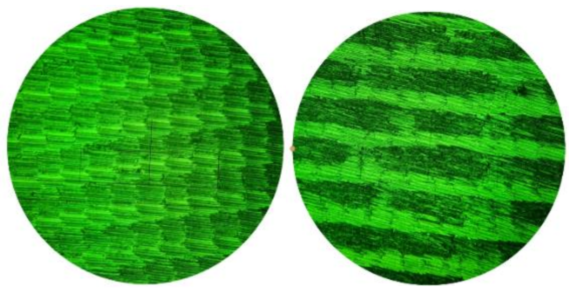
## 3 EXPERIMENTAL RESULTS AND DISCUSSIONS

In the experimental study, two identical test pieces were processed using roughing, semi-finishing and finishing phases. The study follows only the last finishing phase in which the tools with the above geometry and the cutting parameters adopted from the tool manufacturer's catalogue were used.

The experiment recorded the processing time required for surface finishing and the roughness resulting from the processing in the two situations subject to comparison. The results obtained from measurements of Ra roughness are centralized in Table 1 and the microscopic image of the finished surfaces in Figure 8.

*Table 1. Surface roughness*

| Tool | BNEM Ra (µm) | TEM Ra (µm) |
|---|---|---|
| Measured values | 0.603 | 0.826 |
| | 0.686 | 0.747 |
| | 0.463 | 0.691 |
| | 0.564 | 0.832 |
| | 0.559 | 0.647 |
| | 0.645 | 0.567 |
| | 0.631 | 0.615 |
| | 0.595 | 0.719 |
| | 0.478 | 0.650 |
| | 0.519 | 0.904 |
| **Average value** | **0.574** | **0.720** |



**BNEM** **TEM**

*Fig. 8. BNEM and TEM microscop surface images*

As a result of the processing, it was found that a surface with a better roughness in the BNEM milling, Ra=0.574 µm, compared to the TEM milling the resulting roughness being Ra=0.720 µm. Analyzing the two values of roughness, it was found that one of the factors influencing this difference in the value of roughness is the difference in the radius of the cutting edge on the two different surfaces (BNEM – spherical - R=5mm and TEM - toroidal - R=3mm, Fig.5). This difference in roughness is accepted because it falls within the technical conditions of execution of these complex curved surfaces, which is Ra=0.8 µm.

The significant results of this test were in the direction of the processing cost for the two types of tools. For the determination of cost differences, the costs of acquisitions (tools and tool holder) and the actual costs of processing on the CNC center were taken into account. The cost of the BNEM tool is 85.3 € , for TEM is 77.8 € but it is also necessary to purchase a tool holder whose cost is 100 € for all next TEM tools (in normal use).

*Table 2. Process cost for the two different tools*

| No. of parts | BNEM | | | TEM | | |
|---|---|---|---|---|---|---|
| | CNC cost € | Tool holder 0 | | CNC cost € | Tool holder 100 € | |
| | | Tool cost 85.3 € | | | Tool cost 77.8 € | |
| | | 4 tools | Total cost € | | 2 tools | Total cost € |
| 1 | 34.28 | +85.3 | 119.58 | 11.38 | +77.8 | 189.18 |
| 2 | 68.56 | | 153.86 | 22.76 | | 200.56 |
| 3 | 102.84 | | 188.14 | 34.14 | | 211.94 |
| 4 | 137.12 | | 222.42 | 45.52 | | 223.32 |
| 5 | 171.40 | | 256.70 | 56.90 | | 234.70 |
| 6 | 205.68 | | 290.98 | 68.28 | | 246.08 |
| 7 | 239.96 | | 325.26 | 79.66 | | 257.46 |
| 8 | 274.24 | | 359.54 | 91.04 | | 268.84 |
| 9 | 308.52 | +85.3 | 479.12 | 102.42 | | 280.22 |
| 10 | 342.80 | | 513.40 | 113.80 | | 291.60 |
| 11 | 377.08 | | 547.68 | 125.18 | | 302.98 |
| 12 | 411.36 | | 581.96 | 136.56 | | 314.36 |
| 13 | 445.64 | | 616.24 | 147.94 | | 325.74 |
| 14 | 479.92 | | 650.52 | 159.32 | | 337.12 |
| 15 | 514.20 | | 684.80 | 170.70 | | 348.50 |
| 16 | 548.48 | | 719.08 | 182.08 | | 359.88 |
| 17 | 582.76 | +85.3 | 838.66 | 193.46 | | 371.26 |
| 18 | 617.04 | | 872.94 | 204.84 | | 382.64 |
| 19 | 651.32 | | 907.22 | 216.22 | | 394.02 |
| 20 | 685.60 | | 941.50 | 227.60 | | 405.40 |
| 21 | 719.88 | | 975.78 | 238.98 | | 416.78 |
| 22 | 754.16 | | 1010.06 | 250.36 | | 428.16 |
| 23 | 788.44 | | 1044.34 | 261.74 | | 439.54 |
| 24 | 822.72 | | 1078.62 | 273.12 | | 450.92 |
| 25 | 857.00 | +85.3 | 1198.20 | 284.50 | | 462.30 |
| 26 | 891.28 | | 1232.48 | 295.88 | | 473.68 |
| 27 | 925.56 | | 1266.76 | 307.26 | | 485.06 |
| 28 | 959.84 | | 1301.04 | 318.64 | | 496.44 |
| 29 | 994.10 | | 1335.32 | 330.02 | +77.8 | 585.62 |
| 30 | 1028.00 | | 1369.60 | 341.40 | | 597.00 |

Table 2 shows the costs for the two processing situations taking into account the costs arising from the operation of the CNC centre, taking into account the hourly cost CNC-5 axes of 45 euro/hour and the processing times of a part for the two tools of 45'42"/piece for BNEM and 15'11" for TEM, thus resulting in a CNC cost/piece of 34.28 euro in processing with BNEM and 11.38 euros for processing with TEM.

The short processing time with TEM results from the fact that it has six teeth and thus the advance speed is three times higher even if the other cutting parameters are equal. Another advantage regarding the use of the TEM tool is that the tool live of the tool is greater at the toroidal one of 420 minutes than the spherical tool that has a 360 minutes tool live (values given by the manufacturer of the Iscar tool). This difference in durability and processing time of a piece leads to the change of the BNEM tool after 8 parts and the TEM tool after 28 pieces. This aspect is highlighted in Table 2 by marking with the gray color the position corresponding to the tool change and a price jump on the part number 9, 17 and 25 for BNEM and on part number 29 for TEM.

The evolution of costs for the two types of processing is even better highlighted in the graph in figure 9 for a batch of 30 pieces.

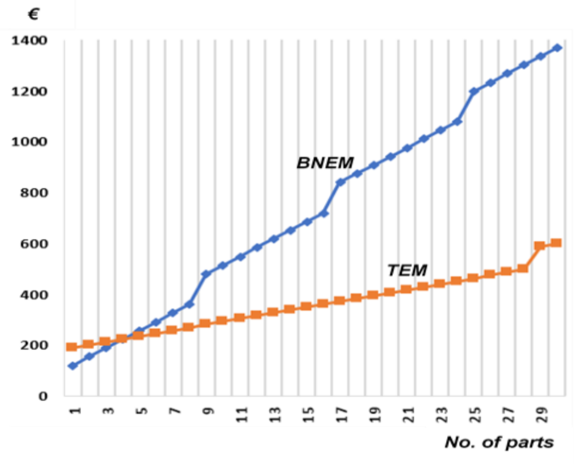



*Fig. 9. The evolution of costs for the two types of processing*

## 3. CONCLUSIONS

The results obtained from this study are very obvious in the sense of obtaining important savings in the process of finishing complex curved surfaces at SC Ramira SA. Only when processing a batch of 30 pieces is obtained a difference of 772.6 € with an average saving rate of about 43 %.

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